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# The contribution of geochronology to Precambrian studies in Western Australia

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## Abstract

In 1906, one decade after the discovery of radioactivity, Rutherford demonstrated that the accumulation of radiogenic daughter products in rocks and minerals containing radioactive elements could be used to calculate their ages. This event initiated the discipline of physical geochronology, whose development and application, outlined in this paper, gradually enabled a firm time scale to be established for the study of earth history. Such a scale had a particularly powerful effect on the study of Precambrian rocks, for which no other effective internal age criteria had been available. The U-Pb, Th-Pb, K-Ar, and Rb-Sr methods were successively developed and refined to produce compatible results of great precision; the mass spectrometer played a key part in this process. In Western Australia, an attempt was made to obtain a mineral U-He age as early as 1910, and data obtained at that time were used in 1926 to calculate U-Pb and Th-Pb ages. But the work was not pursued, and geologists were slow to realise the potential of the new discipline; it was not until the early 1960s, some 10 years after the establishment of the first geochronological laboratory in the State, in the Physics Department of the University of Western Australia, that geologists working on the Precambrian came to appreciate the full value of physical age determinations for their work. Since that time, continuing work at the Australian National University in Canberra, and at the Western Australian Institute of Technology, has combined with the more recent work of other groups to produce a good understanding of the broad geochronological framework of the State. Nevertheless, many problems still remain, but newly developing methods show promise for their resolution.

## Introduction

With the benefit of hindsight it is clear that the introduction, during the first decade of this century, of rock and mineral age determination by methods based on radioactive decay was an event of crucial significance for geology, in that it initiated the systematic constraint of historical geology within a reliable time scale. However, to contemporary geologists the importance of this event was by no means self-evident, and the development of physical geochronology in relation to 'classical' geology deserves wide attention as an example of the complex processes at work in the progress of scientific ideas.

For Western Australia the subject has special interest, both through the importance of geochronology in a State with such a vast area of exposed Precambrian rocks of different ages, and also because certain important conceptual advances in geochronology were made in Perth. In outlining, in a paper of this length, the progress of geochronology in Western Australia and its impact on Precambrian studies, we have had to assume that the reader has an acquaintance with both the geology and geography of the State. Readers lacking this, but nevertheless interested in detailed studies, will find adequate information in both areas in Memoir No. 2 of the Geological Survey (G.S.W.A. 1975); readers of this paper who wish to extend their knowledge of the development of geochronology will find a book compiled by C. T. Harper (1973) of great interest.

## Critical events in geochronology

### *Discovery of radioactivity*

Early attempts to measure geological time were based on such time-dependent phenomena as rates of sedimentation, the rate of cooling of the earth, and the accumulation of sodium in sea water. All these techniques were quantitatively crude, and involved sweeping assumptions, and it was apparent that a new approach to the problem was required. This came about in a curious fashion. In 1896 Henri Becquerel, a French physicist, found that uranium salts placed near a photographic plate in a drawer in his work table had produced an image of a key which was accidently lying on the plate. He realised that the uranium was emitting invisible but penetrating rays—the element was in fact "radioactive".

Rutherford and Soddy, investigating the phenomenon discovered by Becquerel, found that the empirical facts of radioactivity could be explained by assuming that radioactive atoms disintegrated at characteristic rates to form new atoms of other elements. The rate of decay of a radioactive parent to a stable daughter is proportional to the number of parent atoms, N, present. This law of radioactive decay can be expressed as

$$N = N_0e^{-\lambda t}$$

where $N_0$ is the number of radioactive parent atoms present at the time of formation of a mineral or rock, t measures the time elapsed since their formation and $\lambda$ is the decay constant of the radioactive nuclide. It was shown that the decay constant did not vary over extreme variations in the physical environment and has remained unchanged at least over geological time periods.

### *Chemical methods in geochronology*

Lord Rutherford quickly realised that the accumulation of stable radiogenic daughter products, such as helium and lead in uranium bearing minerals, could be used to measure geological time (Rutherford 1906). Unfortunately the only means available at that time to measure helium and lead were chemical techniques, and both these methods had serious shortcomings.

Strutt (1910) showed that helium leaked from uranium-rich ores, even under laboratory conditions, and thus the measured helium ages could only be regarded as minimum estimates. As a result the helium method fell into disuse for nearly 20 years, until Dubey and Holmes (1929) showed that the method could be used to measure the age of common rocks.

After some promising early work on the uranium-lead method by Boltwood (1907) and Holmes (1911), it was realised that radiogenic lead was produced by both uranium and thorium, and since these two elements often occurred together in minerals, it was impossible to disentangle the two decay chains by purely chemical methods. Another problem was the presence of common lead, included in minerals at the time of their formation, which could not be distinguished from the radiogenic lead except by using corrections based on atomic weight determinations. Thus the chemical lead method could only be used for rich uranium-bearing ores and was therefore not applicable to common rocks where the amount of uranium was exceedingly small.

One of the first earth scientists to appreciate the importance of radiometric-based geochronology was Arthur Holmes. He was one of the early proponents of the uranium-lead method, and urged the establishment of a radiometric time scale, and the application of radiometric dating to the crystalline basement rocks of the Precambrian. His book entitled "The Age of the Earth" (Holmes 1927), did much to publicise the emerging field of geochronology, particularly among geologists.

### *Physical methods in geochronology*

A major breakthrough in the extension of geochronology came from a most unexpected direction. F. W. Aston, working almost in isolation at the Cavendish Laboratory, developed a mass spectrograph employing both electric and magnetic fields, which was far more sensitive than earlier versions. By studying the isotopic composition of lead he observed isotopes at masses 206, 207 and 208 (Aston 1927). Aston then analysed a uranium-rich sample of bröggerite and showed that it was highly enriched in lead 206 (Aston 1929). The age reported for this mineral heralded a new era in geochronology, in that this age was based on an isotopic rather than a chemical analysis.

Since that time the mass spectrometer has become the tool of every practising geochronologist—a veritable time machine for the exploration of the past (Harper 1973). Between 1929 and 1941 mass spectrometric techniques developed rapidly, mainly as a result of the work of Alfred Nier at the University of Minnesota. Nier *et al.* (1941) reported the results of isotopic analyses of lead separated from both radioactive and lead ore minerals. The age of one monazite sample gave a $^{207}Pb/^{206}Pb$ age of 2 570 ± 70 m.y., which was the first substantial isotopic evidence of the immense age of the Precambrian. Nier was also instrumental in determining the isotopic composition of uranium (which was a vital factor in atomic energy research), in discovering the geochronologically important isotope $^{40}K$, and showing that radiogenic $^{40}Ar$ could accumulate in potassium-rich minerals (Aldrich and Nier 1948). Nier has rightly been called the "father of modern mass spectrometry".

### *The emergence of new techniques in geochronology*

After a bright beginning early in the present century, geochronology developed slowly. The late 1940s and 1950s however, saw an enormous burst of activity which established the feasibility of the potassium-argon and rubidium-strontium techniques, and extended the traditional U-Pb, Th-Pb method. After World War II isotopically enriched tracers became available, and coupled with further advances in mass spectrometry, enabled very low concentrations of uranium, thorium and lead to be accurately measured. This method of analysis, known as stable isotope dilution, has recently been described by de Laeter and Rosman (1977).

It was now possible to obtain three independent ages from the U, Th-Pb system: $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$ or $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{232}Th$. Wetherill (1956) used a ratio plot of $^{206}Pb/^{238}U$ against $^{207}Pb/^{235}U$ to show that a phase which has remained a closed system to uranium and lead will have $^{206}Pb/^{238}U$ ages equal to $^{207}Pb/^{235}U$ ages, and that the data for systems of different age will lie along a curved line called "concordia". Phases having the same age, and subject to lead loss or uranium gain will, under prescribed conditions, have data that lie along a straight line which intersects concordia. The lower intersection may represent the time of the episodic event and the upper intersection the age of the phase itself. The work of Silver and Deutsch (1963) showed that U-Pb zircon analyses could be used to give the time of original crystallization of metamorphosed Precambrian cratonic areas.

The decay of the radioisotope $^{40}$K to $^{40}$Ar forms the basis of a dating technique which can be applied to rocks and minerals between a few tens of thousand and several billion years old—a broader range than can be determined with other radioactive methods. Because potassium is a common rock-forming mineral and argon is retained in many minerals over geologically long periods of time, most rock types can be successfully analysed by this technique. After the early work by Aldrich and Nier (1948), Reynolds (1956) developed a high-sensitivity mass spectrometer for noble-gas analysis, and a number of studies determined the argon retentivities of a wide variety of geological materials. Application of the K-Ar method to young volcanic rocks has been described by McDougall (1966), whilst the technique has also been used successfully to date the times of reversals of the earth's magnetic field (see for example Cox *et al.* 1968).

However, the K-Ar method had serious shortcomings, most of which were related to the migration of argon in mineral assemblies. Fortunately, a variation of the K-Ar method described by Merrihue and Turner (1966), has enabled the imperfect retention of radiogenic argon, or the presence of excess $^{40}$Ar to be measured. This technique is known as the "$^{39}$Ar method", as it involves the conversion, by irradiation with fast neutrons, of a proportion of the $^{39}$K nuclei to $^{39}$Ar.

Another new technique that emerged at about the same time was based on the decay of $^{87}$Rb to $^{87}$Sr (Hahn and Walling 1938). Eleven years were to elapse before Ahrens (1949) published the results of an extensive investigation into Rb-Sr dating based on a spectrochemical rather than a mass spectrometric technique, and showed that it was possible to obtain ages by the Rb-Sr method.

The problem of separating the very small amount of rubidium and strontium encountered in common rock forming minerals in a form pure enough to analyse in a mass spectrometer was overcome by the use of ion-exchange chemistry (Aldrich *et al.* 1953), enabling common strontium to be distinguished from radiogenic $^{87}$Sr, and accurate mass spectrometric results to be obtained. Throughout the 1950s Rb-Sr dating was applied to micas and feldspars from a number of rocks, and the method gained increasing recognition. Schreiner (1958) then showed that whole rock samples could be used for Rb-Sr dating in addition to mineral separates.

This observation led to a major advance in Rb-Sr geochronology, in that Compston and Jeffery (1959) were able to show that minerals could lose radiogenic $^{87}$Sr some time after crystallisation, but that the radiogenic $^{87}$Sr was still retained by the whole rock itself. The Compston-Jeffery model provided an explanation for discordant Rb-Sr ages and showed that primary crystallisation ages could be determined in addition to metamorphic events in isotopically disturbed systems. Further details of this work are given later in this paper. Nicolaysen (1961) used a simplified graphical method by plotting $^{87}$Sr/$^{86}$Sr against $^{87}$Rb/$^{86}$Sr in which members of a comagmatic suite of igneous rocks which have remained chemically closed to rubidium and strontium form a straight line called an "isochron", the slope of which is related directly to the age of the rocks, while the intercept on the $^{87}$Sr/$^{86}$Sr axis defines the value of this ratio in the magma source region at the time of differentiation. The Rb-Sr method has been used more extensively in Western Australia than any other technique.

### *The impact of modern technology*

In the early 1960s geochronology was hampered by poor analytical precision, and the resulting interlaboratory discrepancies made it difficult to compare results on an international basis. As a result of these problems a number of international standards were produced to assist laboratories in producing data of high quality. For example, the Eimer and Amend standard was distributed widely to laboratories involved with Rb-Sr analyses, and more recently the National Bureau of Standards have produced stoichiometric salts of rubidium and strontium of known isotopic composition. Standard silicate rocks have also been used by many laboratories to check their elemental abundance measurements, so that geochronological data can now be compared with greater reliability than in the past.

Commercial mass spectrometers have also improved considerably over the past decade. Technological advances including solid-state electronics, peak switching, on-line data reduction by minicomputers and high-vacuum technology, have greatly improved the precision and speed at which isotopic ratios can be measured, and expanded the range of geological samples that can be used. Improvements in ion-exchange chemistry and the use of low contamination "clean rooms" have also played a major role in improving the quality of the data, and have allowed problems to be successfully tackled which would have been impossible even ten years ago. One of the factors in this technological revolution has been the Apollo programme. Considerable information concerning lunar chronology has been accumulated by a variety of geochronological techniques, in which technical problems of considerable magnitude have had to be overcome. The experience so gained has been of inestimable value to terrestrial geochronology. A further improvement in the comparison and assessment of geochronological data has resulted from new measurements of the decay constants of $^{235}$U and $^{238}$U (Jaffey *et al.* 1971) and the adoption of a new value of $1.42 \times 10^{-11}$ yr$^{-1}$ for $^{87}$Rb (Steiger and Jager 1977).

## Western Australian geochronology

### *Early ages derived from Simpson's work*

The earliest attempt to determine the age of a Western Australian mineral by a method based on radioactive decay was made by E. S. Simpson, then Chemist and Assayer of the Geological Survey of Western Australia, in 1910 (Simpson 1910, 1911, 1912). Simpson had received, in that year, samples of a bright-yellow ochreous uranium mineral, which he named pilbarite, from a pegmatite at Wodgina, in the Pilbara Block. As he was acquainted with the work of Rutherford and Strutt on the use of helium in age determination, he carefully analysed the material for helium, and calculated an age of 13 m.y.; but he pointed out that as it was a secondary weathering product, and in any case may also have lost radiogenic helium, this age probably had no significance.

At about the same time Simpson also fully analysed two associated uranium minerals from the same pegmatite, which he identified as mackintoshite and thorogummite, parental to the pilbarite. An intriguing question then presents itself as to why Simpson failed to calculate the ages of all three minerals from the amount of lead present. He had determined this, and had specifically commented on its derivation by radioactive decay; he was also generally familiar with the work of Boltwood, for he mentions him by name (Simpson 1912), though he does not refer to Boltwood's 1907 paper.

Whatever the reason for this puzzling omission, fifteen years went by before L. A. Cotton, Professor of Geology at the University of Sydney, used Simpson's published analytical results to calculate chemical lead ages for these minerals, and also for fergusonite from another Pilbara pegmatite at Cooglegong, an analysis of which had by then been published by Simpson (1919). Cotton's (1926) calculated ages of 620, 1 475, 1 460 and 3 840 m.y. respectively for fergusonite, mackintoshite, thorogummite, and pilbarite took account of the lead contribution by thorium. Holmes and Lawson (1927) independently revised Cotton's calculations, and the inclusion of the age of "mackintoshite, etc" as 1 260 m.y. in Holmes' (1927) popular book "The age of the Earth", in which it was the oldest age recorded, placed the significance of Simpson's 1910 analytical work before a wide audience.

It now appears that this age is too low by a factor of at least two, and this makes it even more ironic that it was probably largely due to Holmes' book that a widespread belief arose that the Precambrian of Western Australia contained the most ancient rocks of the Earth's crust.

### *Miscellaneous later results*

Simpson did not maintain his interest in mineral age determination, and in a letter of 1927 on Government Chemical Laboratories files he politely rejected a suggestion from Sir Douglas Mawson that he should recommence such work. Chemical lead age determinations were later carried out, in 1953, by the Chemical Laboratories on two samples of allanite, collected by A. F. Wilson from pegmatites in the Fraser Range and at Doubtful Island Bay (Prider 1955). The ages, of 1 210 ± 50 and 1 390 ± 50 m.y., are in good accord with subsequent K-Ar and Rb-Sr work on biotite (Aldrich *et al.* 1959), as well as with more recent Rb-Sr results (Bunting *et al.* 1976).

These isolated results were not part of a continuing programme, and the same comment applies to a group of ages estimated from the isotopic compositions of galena samples supplied by J. D. Campbell and R. T. Prider to J. Tuzo Wilson, of the University of Toronto, in 1953 (Prider 1955). These were the first results for any Western Australian minerals by a method employing mass spectrometry.

### *Establishment of systematic work in the 1950s*

In 1950, on his way to take up an appointment at the Australian National University, Professor (later Sir) Marcus Oliphant visited the Physics Department of the University of Western Australia, and spoke of the need for an Australian research programme in geochronology, particularly in view of the widespread belief that the continent contained the Earth's oldest rocks (Jeffery 1976). Oliphant had worked with Lord Rutherford in Cambridge, and was familiar with the physical techniques used in geochronology.

As a result, two younger staff members, P. M. Jeffery and A. H. Morton, terminated the construction of a small accelerator and began instead to build a mass spectrometer, intended ultimately for a continuing geochronological programme. Jeffery (1976) has given a graphic account of the difficulties involved. The instrument first operated in late 1952, but its performance was not satisfactory, and during 1953 it was decided to abandon the project unless more financial support could be found. Fortunately, a grant became available from the Carnegie Institute of Washington, sufficient not only to bring the home-made instrument into effective operation but also to provide a second, new, Nier-type mass spectrometer. It was on this instrument, commissioned by D. Greenhalgh, that the first isotopic U-Pb age was obtained from a Western Australian mineral. The tanteuxenite used came from a pegmatite at Woodstock, again in the Pilbara Block, and yielded a maximum age of 2 790 ± 25 m.y. (Greenhalgh and Jeffery 1959).

It was only after Jeffery had taken up a Carnegie Fellowship at the Department of Terrestrial Magnetism in Washington in 1955 that the potential of the Rb-Sr and K-Ar methods was fully appreciated, and on his return to Perth programmes in both these methods were begun. Although a number of K-Ar determinations were carried out on micas and feldspars from pegmatites and granites, the main achievements of the group thus established lay in the Rb-Sr method, in which work Jeffery was joined by W. Compston and G. H. Riley.

Towards the end of the 1950s the validity of the Rb-Sr method was being questioned, since mineral separates from whole rock samples were giving discordant ages. A granite from the Boya quarry near Perth was analysed by Rb-Sr geochronology, together with the biotite and microcline separates. The resultant ages were 650 m.y. for the biotite, 1 290 m.y. for the microcline and 2 430 m.y. for the whole rock (Compston and Jeffery 1959). The authors suggested that the mineral separates had lost a significant proportion of their radiogenic Sr some time after crystallisation, after which metamorphic events caused the Rb-rich minerals to lose radiogenic $^{87}$Sr which was simply redistributed within the whole rock system.

The model proposed by Compston and Jeffery represented a most important advance in the interpretation of discordant Rb-Sr ages and established the Rb-Sr technique as a powerful tool in geochronological studies of isotopically disturbed systems (Harper 1973). Fairbairn *et al.* (1961) applied the Compston-Jeffery model to a number of discordant ages from Sudbury in Canada, and concluded that "we therefore regard the whole-rock approach as a milestone in interpretation of discordant Rb-Sr data". The Compston-Jeffery model was elaborated in a number of important publications (Compston *et al.* 1960, Riley and Compston 1962, Riley 1961) which set the seal on this contribution by the laboratory.

An important geological contribution to the programme was made by A. F. Wilson, of the Geology Department of the University of Western Australia. His energetic research interests in the southern Yilgarn Block, and in the Albany-Fraser Province, were a significant control over the material selected for analysis. The seminal 1960 paper by Wilson, Compston, Jeffery and Riley (Wilson *et al.* 1960), in which 36 Rb-Sr ages (19 of them new), 16 K-Ar ages (4 new), and 21 U-Pb ages were presented and discussed together was the first systematic attempt to relate these results to the tectonic evolution of the Western Australian, and in this case also the Australian, Precambrian. Even so, their potential in this respect was restricted, since apart from mineral ages from isolated pegmatites of uncertain geological relationships in the Halls Creek Province, the Pilbara Block, the Northampton Block, and the Albany-Fraser Province, the reported ages were confined to the southern parts of the Yilgarn Block; the main factor in the choice of the pegmatite minerals was, necessarily at that stage, their chemical suitability.

### *The changed situation of the 1960s*

In 1959 it might have been supposed that all was set for a major expansion of geochronological work at the University of Western Australia, but in fact by 1961 such work had ceased (Jeffery 1976). The prime reason for this was probably a growing appreciation, from the practical experience gained, that the establishment and maintenance of a geochronological laboratory of the size and scope that was needed in Australia was, quite simply, an inappropriate task for a comparatively small Physics Department which wished also to retain a range of representative research interests. The decision to terminate such a successful research programme was made easier by a concurrent move by the Australian National University to establish a laboratory better equipped to supply national needs in Canberra, in association with the Commonwealth Bureau of Mineral Resources. Compston moved to that laboratory in 1961, while Riley took up a research fellowship at the Australian Institute of Nuclear Science and Engineering in New South Wales. Coincidentally, Wilson, the major geological contributor in the group, simultaneously moved to Queensland, and "a comprehensive geologic age determination programme which is being developed to outline the geochronology of the Australian continent" (Greenhalgh and Jeffery 1959) was abruptly discontinued.

That Precambrian geochronological studies in Western Australia were not disastrously set back by this event is wholly due to the fact that, from Canberra, Compston retained a strong interest in Western Australian work. This was effectively achieved by initiation of Ph.D. studies in restricted areas, and theses which were completed or initiated in this way during the 1960s include those of Turek (1966), Bofinger (1967), Worden (1970), and Gray (1971). During this period Compston maintained a good liaison with the Geological Survey of Western Australia, and some results were published in association with it (Leggo *et al.* 1965). In respect to Western Australian work, he also joined in geological liaison with other university departments, and encouraged such liaison among his students and colleagues, so that consequent publications result from a wide range of collaborative work.

Two characteristics differentiate the Western Australian work carried out from Canberra in the 1960s from the earlier Perth work. Firstly, the necessity for close integration of field geology and geochronological studies was recognised. The work of Bofinger (1967) on the eastern arm of the Halls Creek Province provides a typical example of this: as a member of the Bureau of Mineral Resources, Bofinger took part in the joint field mapping with the Geological Survey of Western Australia, and collected and observed the geological relations of almost all of the samples he analysed. Secondly, and as a consequence of this recognition, an attempt was made to extend geochronological work more widely over the Western Australian Precambrian. Thus from work during this period results were obtained from the Kimberley region (Bofinger 1967, Bennett and Gellatly 1970), from the Pilbara Block (Arriens 1967, Compston and Arriens 1968), from the Hamersley Basin (Leggo *et al.* 1965), from the Gascoyne Province (Compston and Arriens 1968), from the Bangemall Basin (Compston and Arriens 1968), from the Musgrave Block (Compston and Nesbitt 1967, Gray 1971), from the Albany-Fraser Province (Arriens and Lambert 1969, Turek and Stephenson 1966), from the Yilgarn Block (Turek 1966, Worden 1970) and from 'basement' rocks encountered in petroleum exploration drilling in the Officer Basin (Bofinger 1966), and the Canning Basin (Johnstone 1961). A noteworthy early publication of this period recorded a pioneer attempt to establish the depositional age of a shale by the Rb-Sr method (Compston and Pidgeon 1962).

### *Consolidation in the 1970s*

It was this emphasis on the integration of field geology and geochronology that brought home to the bulk of geologists concerned with the Western Australian Precambrian in the 1960s that isotope geochronology had become an indispensable tool for the solution of many problems, and a positive demand for results began to grow. Two main factors made it seem unlikely that Compston's laboratory alone could satisfy this. These were, firstly, the constraining effects of the need to define most work in terms of independent higher degree parcels, and an increasing commitment of the laboratory to prepare for and carry out work on returned lunar samples, first received after the USA Apollo 11 mission in 1969.

In response to this situation, we discussed, early in 1968, as representatives of the Physics Department of the Western Australian Institute of Technology (JRdeL) and of the Geological Survey of Western Australia (AFT), the possibility of establishing a co-operative geochronology programme based on mass spectrometric facilities already in operation at the Institute of Technology. The ranges of geological and physical expertise within the respective groups appeared to be potentially complementary, and it was agreed to proceed on a trial basis, with a number of restricted projects.

For these initial projects rock bodies were chosen for which clear-cut geological relationships indicated the likelihood that they would each yield a single age of known significance; and a further restriction was applied that each should be chemically amenable to a whole-rock Rb-Sr isochron approach, using for each sample a combination of X-ray fluorescence analysis of the Rb/Sr ratio and a single unspiked mass spectrometer run for the $^{87}$Sr/$^{86}$Sr ratio. One final constraint on project choice should not be overlooked: close liaison was maintained with the Australian National University geochronological laboratory to avoid duplication of work, and this liaison was also crucial in the establishment of experimental procedures.

The anticipated mutual advantages in co-operation between the Geological Survey and the Institute of Technology were amply confirmed in practice. The first results were published in 1970 (de Laeter and Trendall 1970), and a total of 19 papers have appeared from a currently continuing programme. The basic restriction to the Rb-Sr method has been maintained throughout, but no problem which could be theoretically solved by the method is now excluded by analytical constraints, although regard in planning is paid to the desirability of maintaining an acceptable ratio of geologically meaningful results to invested analytical time.

Two important controls over the choice of problem to attack have been the progress of the Geological Survey regional mapping programme, and the conscious attempt to identify priority areas, in which work seems likely to yield the most productive results. Work published so far has been widely distributed over the State, and includes results from the Pilbara Block (de Laeter and Trendall 1970, de Laeter and Blockley 1972, de Laeter *et al.* 1975, Lewis *et al.* 1975, de Laeter *et al.* 1977), from the Hamersley Basin (de Laeter and Trendall 1971, Trendall and de Laeter 1972, de Laeter *et al.* 1975, Hickman and de Laeter 1977), from the Yilgarn Block (Muhling and de Laeter 1971, Bunting *et al.* 1976), from the Paterson Province (Trendall 1974), from the Gascoyne Province (de Laeter 1976), from the Bangemall Basin (Gee *et al.* 1976) and from the Albany-Fraser Province (Bunting *et al.* 1976).

Although we have chosen to regard the re-establishment of geochronological work in Perth as the distinguishing character of the 1970s we emphasize that there was no termination of Canberra work. This continued through the 1970s with the same general policy and objectives that had applied before. However, a significant innovation during this period was the initiation of Pb-Pb work on trace lead in minerals (Oversby 1976), and subsequently of the U-Pb method on extracted zircons. It is a special objective of this work to identify the oldest rocks of the Australian continent. The 3 450 m.y. age for dacite of the Duffer Formation, in the Pilbara Block, recently published by Pidgeon (1978), is the oldest age so far determined from the Archaean of Australia; Pidgeon's continuing work on zircons will be an important addition to Western Australian geochronology. Some work on Western Australian material was initiated and carried out by the Bureau of Mineral Resources in Canberra during the 1970s (Page *et al.* 1976).

In addition to the continuing geochronological programmes in Perth and Canberra, which we have discussed in some detail, the 1970s saw the initiation of some Western Australian work by other laboratories. A mass spectrometry unit established at the Department of Geology of the University of Adelaide in 1972 has published Rb-Sr results from the eastern Yilgarn Block (Cooper *et al.* 1976), and has also worked in the Pilbara Block. Yilgarn Block Rb-Sr results have also come from commercial laboratories in Adelaide (Webb and Watts 1975), some K-Ar work on the Albany-Fraser Province has been carried out at the University of Queensland (Stephenson *et al.* 1977).

The University of Melbourne has a varied programme of geochronological research in Western Australia, concentrating mainly on fission-track techniques, but including ion-probe isotope geochronology; no results have been published at the time of writing. The CSIRO Division of Mineral Physics also has current plans for both Rb-Sr and Sm-Nd studies on Western Australian material.

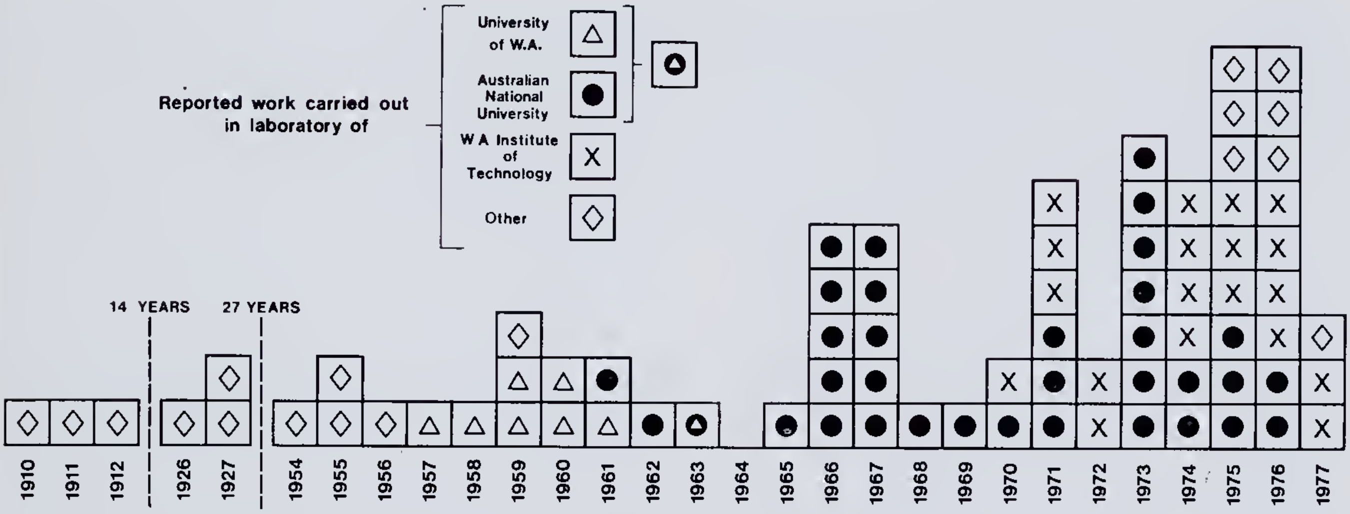

Figure 1.—Chronological summary up to 1977 of all publications including first reports of ages of Western Australian Precambrian rocks and minerals by methods based on radioactive decay. Selected second reports are also included where these augment or upgrade the first.

Thus, at the time of writing, five geochronological laboratories have continuing programmes in Western Australian, while other work is being carried out from time to time. Current planning has the advantage of a reasonably well established time-scale of years for the evolution of the Precambrian rocks.

*Publication summary*

We have elsewhere presented a complete listing of all first, and some subsequent, publications reporting the results of geochronological work on the Western Australian Precambrian (Trendall and de Laeter 1978). Figure 1 is a graphical summary of the 77 such papers there included. It reflects clearly the phased development of geochronological work described above.

## Interaction with geological work

This brief account of the interaction of geochronology with general geological studies must accept, so far as geology is concerned, various review papers as representative of the thinking at the time of their appearance. The situation shortly before the advent of geochronology was well summarised by the then Government Geologist, A. Gibb Maitland (1906). He assigned all "those gneissic, granitoid, and schistose rocks, which" . . . "form the floor upon which the newer strata have been laid down" to the Archaean; his next younger time division was the Cambrian, within which were included, under the name "Nullagine", many of the younger, unaltered, and undeformed sediments, now known to have a wide range of Precambrian ages.

Naive as this view may now seem, a modified form of it persisted until its final concurrent destruction by mapping and geochronology in the 1960s. The modification consisted in accepting a two-fold time division of the Precambrian into an older Archaeozoic (Archaean) and a younger Proterozoic; rocks of the two ages were normally separated by a major unconformity. This modified time classification was used, for example, by Maitland (1919) in a subsequent summary of the geology; in this summary Maitland made no reference to Simpson's (1911, 1912) published attempt to determine the age of uranium-bearing minerals.

In 1930 E. de C. Clarke reviewed the Precambrian geology of the State in a Presidential Address which was published in the following year (Clarke 1931) and illustrates well certain points we wish to emphasize here.

Firstly, Clarke (1931, Table p. 187) essentially accepted the two-fold division of the Precambrian, with a "Great unconformity" dividing various older rocks below from the "Nullagine Series" above. Secondly, the Nullagine Series was correlated between widely separated areas of the State with no Precambrian outcrop continuity—specifically between the Meekatharra, Kimberley, and Warburton areas, and by implication the Nullagine district itself.

Thirdly, although Clarke noted that "there is no certainty in correlating similar rocks of the different districts, many of which are widely separated", he also stated that "Correlation" . . . "can only be made after much fresh petrological detail combined with field observations is available". Like Maitland, he did not refer to Simpson's results, nor did he give any indication either of being aware of Cotton's (1926) or Holmes' (1927) calculated ages from them, or of appreciating the potential value of age determinations based on radioactive decay.

These three points, and among them we emphasize the third, apply to all general reviews of the Precambrian geology of Western Australia published during the 20 years following Clarke's (for example: Forman 1937, Clarke 1938, McKinstry 1945, Prider 1948). Thus Holmes' publication in 1927 of the Wodgina age, on the basis of Simpson's 1910 analyses was met within Western Australia by a total lack of *published* reaction.

The first published reference to the important potential of geochronology for Precambrian correlation in Western Australia was made by Prider (1952), in a summary of the geological structure of the southwestern part of the State. However, two more years passed before Prider (1954) made the *first published reference within Western Australia* to Holmes' (1927) calculation of an age from Simpson's analyses, in a review that summarized all available geochronological information to that date.

In the absence of locally published comment between 1927 and 1952 it is not easy to establish whether Holmes' publication of the Wodgina age was in Western Australia largely overlooked, or whether it was generally known, but not taken very seriously. For information on this point we are indebted to Mr. F. G. Forman. Forman (pers. comm. 1978) is emphatic that Holmes' work was well known to geologists working on the Precambrian at that time, but that there was widely and deeply felt mistrust of the reliability of radiometric age determinations. Prider has pointed out to us that an unpublished handbook to accompany historical geology lectures at the University of Western Australia in 1939 referred to an age of 1 260 million years from a pegmatite in the North-West, although no authority was cited. We accept that the lack of published references to Holmes' (1927) work was not due to lack of either knowledge or interest, but to a doubt shared by most geologists as to its validity. The same feeling is probably echoed for Australia generally by David and Browne (1950), who mentioned the Wodgina age, without citation, and with the unelaborated comment (p. 4) "the results are not regarded as reliable".

After Prider's (1954) first listing of available geochronological results, quickly followed by that of Wilson (1958), the application of geochronological results became common among Precambrian geologists in Western Australia. However, the earlier mistrust in them took some time to diminish, and although individual geologists, notable among them A. F. Wilson, enthusiastically advocated their utility, general acceptance by the majority of geologists working on the Precambrian was finally achieved only when the results were evidently consistent with the time relationships demonstrable from traditional kinds of geological evidence. The best such example is the demonstration by Geological Survey regional mapping during the early 1960s (Halligan and Daniels 1964) that two sedimentary successions, traditionally correlated as "Nullagine", were separated by a major regional unconformity related to intense folding and metamorphism of the older; later geochronology (Compston and Arriens 1968) confirmed this time relationship. Elsewhere within Australia a similar demonstration of the concordance of geological and geochronological evidence was given by McDougall *et al.* (1965).

## Comment, discussion, and the future

From the sequence of events we have traced above, a picture emerges for Western Australia of the reluctant acceptance of physical geochronology by a sceptical geological community, as a result of the initiative and enthusiasm of physicists and chemists. Simpson's attempt in 1910 to obtain a U-He age for "pilbarite" was in the vanguard of contemporary international effort, but was not locally appreciated as such. The discovery by Cotton and Holmes, after an interval of more than 15 years, that Simpson's published analyses could be used to calculate chemical lead ages, met a similarly cold response.

We initially found it hard to account for this indifference by geologists, especially during the quarter of a century between 1927 and 1952, to results that, judged on their presently known merits, might be assumed to have been challenging and exciting. For a possible explanation we are indebted to Burchfield (1975), who has traced, in an international context, the bitter dispute concerning the age of the earth that continued through the latter part of the nineteenth century between physics, in the person of Lord Kelvin, and geology. Kelvin, from thermodynamic arguments, proposed a severely restricted age, which geologists, from a variety of uniformitarian considerations, could not accept.

The discovery of radioactivity undermined Kelvin's arguments, and discredited, in the eyes of geologists, the reliability of theoretical physical reasoning as applied to the age of the earth. It was ironic that, within a decade of its discovery, this very phenomenon, that had finally justified half a century of spirited geological opposition, became the basis for physical estimates of the age of the earth which were now unacceptably long, rather than too short. Unhappy to embark on a further half-century of debate, "most geologists simply ignored the new physical results" (Burchfield 1975, p. 179). We accept the apparent indifference of most Western Australian geologists to geochronology as a microcosm of this international situation; it was in essence a negative reaction to the earlier failure of physics, as perceived by geologists, to make a helpful contribution to the problem of the age of the earth.

It is all the more remarkable, in view of this indifference, that the geochronology group established at the Physics Department of the University of Western Australia, was so outstandingly successful, in any terms in which scientific attainment is measurable; its achievements are one of the highlights in the history we have traced in this paper. From discussion with many of those concerned, we conclude that its success cannot be ascribed to any single factor, but that a fortuitous coincidence of many unrelated circumstances combined to produce the final result. Apart from the chance visit of Oliphant, it was fortunate that his suggestion was taken up by a leader, Jeffery, whose infectious enthusiasm was vital to attract and sustain the interest of able and dedicated students such as Compston, Greenhalgh, and Riley. The prior existence of instrumental skill within the Department was a further prerequisite for success, as was the availability of emergency finance in 1953 when the project was all but abandoned. Finally, it was significant that

Precambrian granitic rocks with an age of about 2 600 m.y. which had been affected by a thermal overprint at about 600 m.y. were available for study. It was the challenge of this situation that produced the Rb-Sr total rock method, which in turn established the laboratory as an international leader in geochronology.

Burchfield (1975, p. 216) has commented that "From the time when Kelvin coupled the first announcement of his results to an attack upon uniformitarianism, until the final acceptance of radioactive dating nearly seventy years later, the question of the earth's age was never entirely free from some degree of tension between physics and geology". Our examination of the Western Australian situation suggests that, although there were earlier exceptions to which reference has been made, the complete reconciliation of geology and physics in this area did not come until the 1960s. The complete fusion of geological and physical skills is now widely accepted, and unreservedly so by us, to be a prerequisite for effective research in geochronology, and it is interesting that this is true both in current practical experience, and in the context of history.

It is inevitable that a historical examination of the kind we have attempted here should lead us to look at the future. There are at least 16 primary natural radioactive nuclides (Rankama 1963), 5 of which have been extensively used in Precambrian geochronology: $^{40}$K, $^{87}$Rb, $^{232}$Th, $^{235}$U and $^{238}$U. In Western Australia, the $^{87}$Rb-$^{87}$Sr decay system has provided the main basis for establishing the broad time framework which is now known with some confidence. There is much current interest in U-Pb and Th-Pb methods, and the application of these, particularly to zircons and other minerals, is likely to increase. Among the remaining possibilities $^{187}$Re and $^{176}$Lu have been partially developed as geochronometers (Hirt *et al.* 1963, Von Herr *et al.* 1958), but have not yet been applied to Western Australian samples. The decay of $^{147}$Sm to $^{143}$Nd is currently emerging as a decay scheme with the special advantage of "seeing through" severe geological disturbance of a sample (McCulloch and Wasserburg 1978), and it is likely that this method will be applied to the Western Australian Precambrian in the near future.

The radioactive clocks, which are the key to our understanding of the chronology of the earth, have progressively yielded their secrets as technological developments have enabled minute quantities of the radioactive elements and their daughter products to be measured with ever greater accuracy and precision. There seems to be no reason to doubt that further refinements are possible as an ever-increasing number of chronometers are available singly or in combination to tackle the problems of Precambrian geology.

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